

A LOAD PULL SYSTEM WITH HARMONIC TUNING

Current power amplifier designs face a number of challenges. For mobile applications battery life and efficiency are critical. Future designs are anticipating 3 V and lower voltage rails, and digital modulation formats are placing unique requirements on linearity or adjacent-channel power. To overcome these challenges, a harmonic tuning capability has been added to the model LP1 load pull system.¹ This new capability allows characterization of devices as a function of their harmonic and fundamental terminations.

CURRENT MEASUREMENT SYSTEMS

Current measurement systems perform load pull measurements with relative levels of ease of use, accuracy and throughput. However, the systems make their measurements as a function of the fundamental load impedance only. Only the vector passive approach has demonstrated commercially viable harmonic tuning. Table 1 lists the attributes of several commercially available measurement architectures.

FUNDAMENTAL VS. HARMONIC TERMINATION

In the past, the most successful characterization technique for class A amplifier design has been the fundamental load pull technique. To day's applications and their demands of efficiency require other classes of bias, such as AB and B. The efficiency and linearity performance under these bias conditions is a function of the termination presented at the harmonics of the frequency of interest.

The harmonic match's influence on a transistor's performance can be understood by examining the terms in the trigonometric expansion of a two-tone stimulus showing the contribution of the second harmonic and its contribution to distortion performance. The third-order intermodulation (IM₃) products of two tones, F_1 and F_2 , exist at the frequencies $2F_1 - F_2$ and $2F_2 - F_1$. The impedance at $2F_1$ and $2F_2$ influences the amount of signal produced.

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TABLE 1 CURRENT MEASUREMENT ARCHITECTURES			
Measurements	S-parameters, power efficiency, IM, ACP, fixed P _{out} , AM/PM	S-parameters, power efficiency, fixed P _{out} , AM/PM	Power efficiency, IM, ACP
Harmonic tuning	Yes	No	No
Speed	Fast 10 meas/sec	Fast 10 meas/sec	Slow 30 meas/sec
Tuner repeatability	Two parts in 10 ⁵ or < 90 dB residual	N/A, accuracy dependent on automatic network analyzer	40 dB must be recalibrated frequently
System power	> 30 W as a complete system	1 W	Tuners 100 W, no system spec.
Reflection coefficient at 890 MHz	0.9	1.0	0.9 or better depending on bandwidth
Calibration method	In-situ	In-situ	Multistep, de-embed
Bias capacity	Built in, 6 A, 100 V	Built in, 500 mA, 15 V	None supplied

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PRODUCT FEATURE

If a transistor is generating power at frequencies other than the desired fundamental, energy is wasted and efficiency is reduced. The proper termination applied to a transistor at the harmonics of the frequency of interest will then influence the generation of power at the harmonics and therefore, efficiency and linearity. In addition, the magnitude of these effects increases with the nonlinearity of the bias class.

When load pull measurements from various systems are compared, significant differences in the data are observed. In many cases, these differences have been explained away as drift, calibration or other system errors. However, it is probable that some of the differences are due to the effect of the harmonic termination.

These harmonic effects portend the need for control of the harmonic termination in load pull measurements. Attempts at achieving this control have been made in the academic environment and in home-grown applications. One approach is to place a diplexer at the output of the device under test (DUT), as shown in **Figure 1**, allowing the control of one harmonic. Limitations of the diplexer approach are a significant reduction of the tuning radius that a passive tuner can present at the DUT reference due to the loss in the diplexer, and a significant increase in the cost and complexity of the measurement system. An active load pull approach could eliminate the magnitude of the reflection coefficient issue, but would reduce the distortion measurement capability

greatly and necessitate a duplication of the entire active test set. Duplicating the test set is complex and costly, limits the tuning to just one harmonic and has not yet been demonstrated in any practical way.

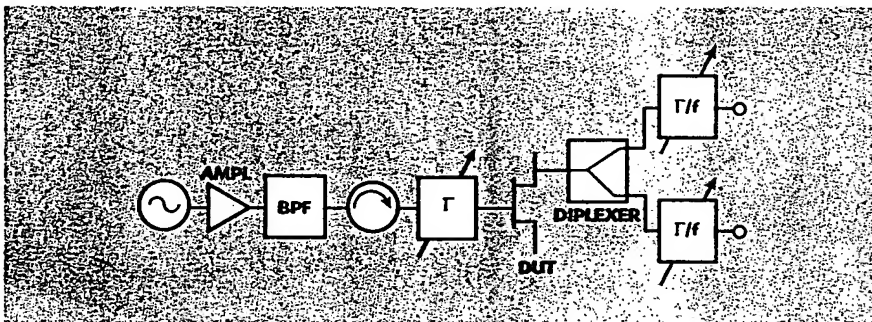
HARMONIC TERMINATION AND THE LOAD PULL SYSTEM

A solid-state, tuner-based load pull system has been developed that overcomes these limitations and performs simple, practical, cost-effective multi-harmonic load pull. The LP1 harmonic tuning system is based around a new generation of solid-state tuner design. The new tuner has metrology-level repeatability (-94 dB residual), 30 W distortion-free power capacity and microsecond switching speed. The tuner also has been enhanced to allow multiharmonic tuning by increasing the number of tuner states exponentially. Each state is a setting of the tuner, which presents a given impedance that varies with frequency. The solid-state harmonic tuner can generate close to half a million different states. The benefit of this number of states lies in redundancy, not quantity, since measurements at that many points would not be made normally.

With that many settings available to the tuner, many states exist that have virtually identical impedances at any given frequency. Due to the inherent nonlinear way the tuner creates its impedances, states that have the same impedance at a given fundamental disperse their impedances at the harmonic frequencies. The tuning system takes advantage of this phenomenon to present a number of different harmonic terminations for any given fundamental, or a variety of fundamentals for any given harmonic. This multiple-state capability allows multiharmonic tuning using a single tuner without the reflection coefficient limitations of a diplexer. **Figure 2** shows the new LP1 harmonic tuning measurement system.

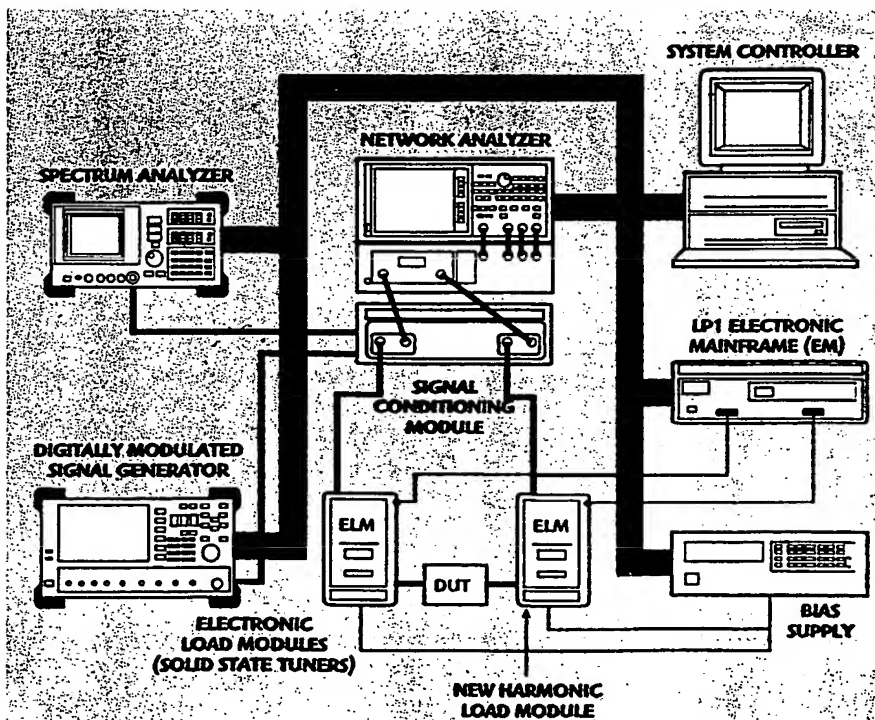
HARMONIC LOAD PULL CHARACTERIZATION OF A TRANSISTOR

As an example, a FET was load pulled conventionally on wafer at 101 states (fundamental control only), for



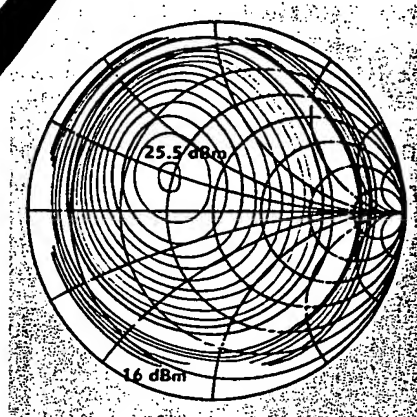
▲ Fig. 1 Previous harmonic tuning using a diplexer.

Fig. 2 The upgraded system platform. ▼

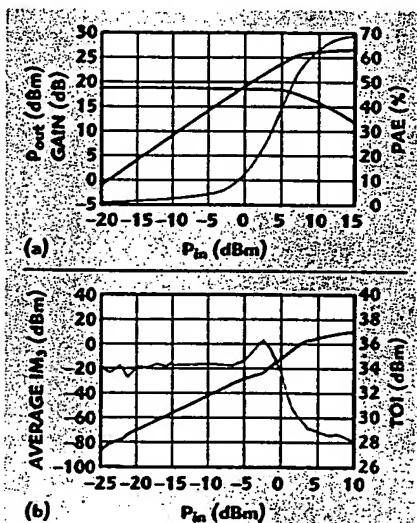


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PRODUCT FEATURE



▲ Fig. 3 Power output contours resulting from conventional load pull at 10 dBm input power.



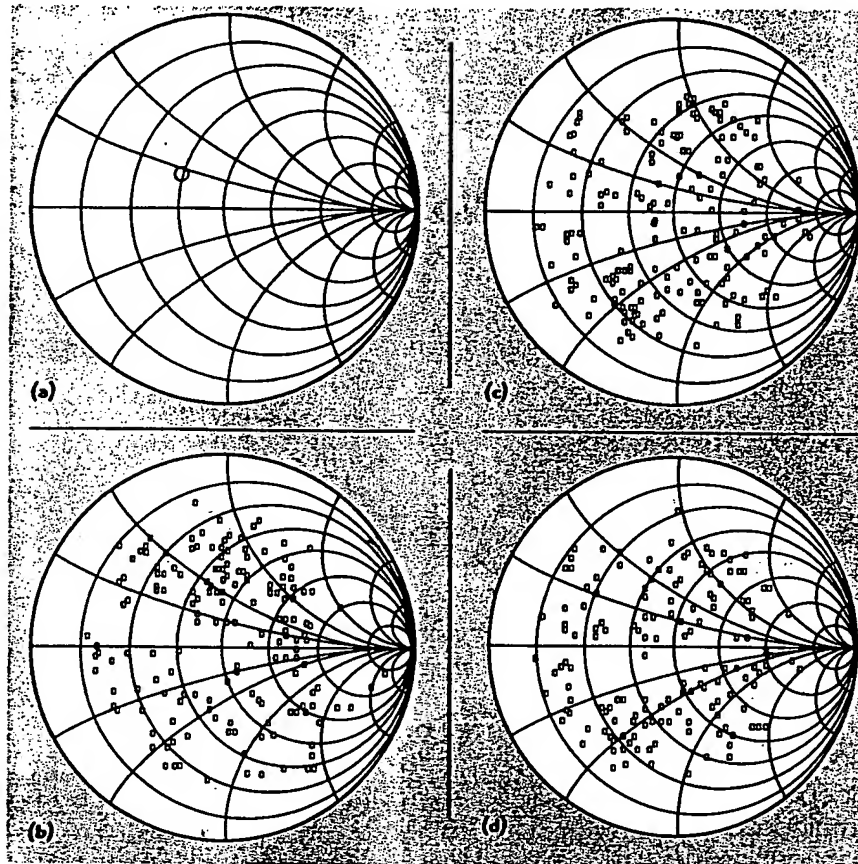
▲ Fig. 4 Conventional load pull results; (a) P_{out} , gain and efficiency, and (b) IM_3 and TOI vs. P_{in} .

TABLE II

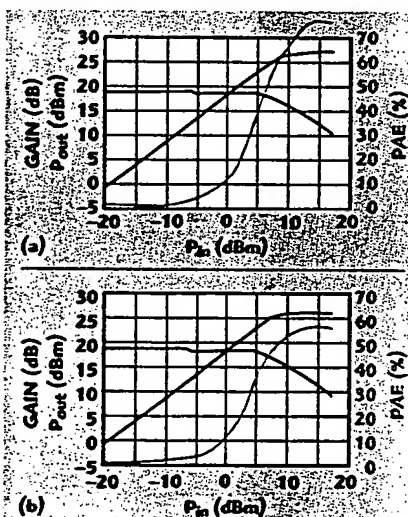
HARMONIC TUNING PERFORMANCE

Best case	25.8	70.8	37.2
Worst case	24.8	51.6	34.2

maximum power output at 1.9 GHz. All measurements were referenced at the probe tip. The power contours and P_{in}/P_{out} plots for power, power-added efficiency (PAE) and IM_3 are shown in Figures 3 and 4, respectively. Contouring indicated an impedance of $0.31 \angle 145^\circ$ as the optimum. Using harmonic tuning capability, the system found 252 different settings of the output tuner that had the same impedance (± 0.02 radius). The on-wafer impedance distribution of these states at the second, third



▲ Fig. 5 The harmonic impedances taken at the probe tip; (a) fundamental, (b) second, (c) third and (d) fourth harmonics.



▲ Fig. 6 The effects of harmonic tuning on PAE: (a) best case and (b) worst case.

and fourth harmonic of 1.9 GHz are shown in Figure 5.

The device was then load pulled with these 252 states of constant fundamental, but the harmonic impedance was varied. Due to the variance of the second-, third- and fourth-harmonic terminations, the device behaves differently in each of the measurements. Table 2 lists the

data on the P_{in} vs. P_{out} plots. Figure 6 shows the effects of harmonic tuning on PAE.

These results indicate the effect of harmonic termination on output power, PAE and third-order intercept (TOI). A conventional load pull measurement yielded values between these two extremes, but these values are not truly optimum for the device.

The ability to extract an additional 10 percent PAE or a few dB in TOI is essential to meet the specifications of today's communication systems. The concept of load pull is to provide the data necessary to optimize transistor development or amplifier design. The LP1 load pull system with harmonic tuning is the first commercial instrument to realize the potential of this measurement fully.

References

1. "A Load Pull System for Digital Mobile Radio Power Amplifiers," *Microwave Journal*, March 1995, pp. 116-118.

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